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14. ABSTRACT
We have demonstrated room temperature error free data transmission up to 40 Gb/s for our Microcavity Laser and 20 Gb/s for Transistor Laser. In order to characterize the our laser devices at data rate > 50 Gb/s, the current instrument limitations need to be overcome. Hence we plan to get higher speed pattern generator and sampling oscilloscope modules. Under the Army Research Office (ARO) contract W911NF-13-10287, we have purchased the SHF 1001A mainframe module, which includes SHF 12103A Dual Channel Differential 56 Gb/s Bit Pattern

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UU	UU	UU	UU		Milton Feng
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Report Title

Final Report: Data Modulation Test Equipment for Microcavity Transistor Lasers

ABSTRACT

We have demonstrated room temperature error free data transmission up to 40 Gb/s for our Microcavity Laser and 20 Gb/s for Transistor Laser. In order to characterize the our laser devices at data rate > 50 Gb/s, the current instrument limitations need to be overcome. Hence we plan to get higher speed pattern generator and sampling oscilloscope modules. Under the Army Research Office (ARO) contract W911NF-13-10287, we have purchased the SHF 1001A mainframe module, which includes SHF 12103A Dual Channel Differential 56 Gb/s Bit Pattern Generator and SHF 78210B Synthesized Signal Generator, and Agilent 86107A-040 Precision Time Base Module. With the new instruments, we were able to characterize the signal integrity of our laser devices up to 56 Gb/s.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
09/04/2014	1.00	Rohan Bambery, Curtis Wang, Fei Tan, Milton Feng, Nick Holonyak, Jr.. Single Quantum-Well Transistor Lasers Operating Error-Free at 22 Gb/s, To be submitted for publication (09 2014)

TOTAL: **1**

Number of Manuscripts: 5

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Curtis Wang	0.00	
Michael Liu	0.00	
Fei Tan	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Milton Feng	0.50	No
Nick Holonyak Jr.	0.50	Yes
FTE Equivalent:	**1.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Rohan Bambery	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Data Modulation Test Equipment for Microcavity Transistor Lasers

Final Report

August 1st 2013 – July 31st 2014

Contract: W911NF-13-1-0287

Submitted to:

U.S. Army Research Office

By:

Principle Investigator, Dr. Milton Feng

University of Illinois at Urbana Champaign

Data Modulation Test Equipment for Microcavity Transistor Lasers

(Final Report on Army Research Office under Grants W911NF-13-1-0287)

Abstract

We have demonstrated room temperature error free data transmission up to 40 Gb/s for our Microcavity Laser (μCL) and 20 Gb/s for Transistor Laser (TL). In order to characterize our laser devices at data rate > 50 Gb/s, the current instrument limitations need to be overcome. Thus, we plan to get higher speed pattern generator and sampling oscilloscope modules. Under the Army Research Office (ARO) contract W911NF-13-10287, we have purchased the SHF 1001A mainframe module, which includes SHF 12103A Dual Channel Differential 56 Gb/s Bit Pattern Generator and the SHF 78210B Synthesized Signal Generator, and Agilent 86107A-040 Precision Time Base Module. With the new instruments, we were able to characterize the signal integrity of our μCL up to 56 Gb/s.

Organization of Report

In this report, we outline the research progress we have achieved so far with the awarded grant, **$200,000** under the Army Research Office (ARO) contract W911NF-13-10287 and **$6,456.30** from UIUC-HSIC grant support for a total purchase equipment budget of $**206,456.30**. The main structure of the report is listed below.

I. Data modulation testing equipment purchased and received
II. Equipment specifications overview
III. SHF 12103A Bit Pattern Generator (BPG) instrument calibration and HSIC high speed VCSEL performance

I. Data modulation equipment purchased and received

We have purchased and received the Agilent 86107A-040 precision reference time base module and the SHF 10001A Mainframe, with embedded SHF 78210B Synthesized Signal Generator with jitter injection option and SHF 12103A 56 Gb/s Dual Differential Channel Bit Pattern Generator (BPG). The detailed price breakdown is shown in Table I below.

Equipment	Price
Agilent 86107A-040 Precision Time Base Module	$21,603.50
SHF 78210B Synthesized Signal Generator & Jitter Inject	$15,333.12
SHF 12103A Dual Differential Channel 56 Gbps Pattern Generator	$155,433.76
SHF 10001A Mainframe	$14,065.92
Total	**$206,456.30**

Table I. Detailed price breakdown of the data modulation testing equipment purchased by HSIC under the ARO contract W911NF-13-1-0287 and UIUC-HSIC grant.

With the listed equipment, we are able to characterize the single-ended signal integrity of μCL and TL with data modulation above 50 Gb/s. The dual channel capability of the BPG allows us to achieve data rate above 100 Gb/s by multiplexing the data from both channels. Also, we are also able to test the signal mixing properties of TL by delivering dual channel data signals to the TL dual base input design. In addition, we are able to investigate the high speed collector feedback linearization. All of the testing we are capable of doing now will facilitate the next generation HSIC high speed device design, which ultimately leads to energy efficient high speed optical communication and computing.

II. Equipment Specification Overview

In this Section, we will highlight the key specifications of the purchased equipment, particularly the Agilent 86107A-040 Precision Time Base Module and the SHF 12103A 56Gb/s Dual Differential Channel Bit Pattern Generator.

II 1. Agilent 86107A-040 Precision Time Base Module

Figure 1: Agilent 86107A-040 Prevision time base module.

When characterizing high speed devices with modulation capability higher than 40 Gb/s, a minimal amount of inherent scope jitter can be significant as a 40 Gb/s waveform only has a bit period of 25 ps. A scope jitter of 1 ps RMS can result in 6 to 9 ps jitter, which is more than 20% of the bit period of a 40 Gb/s waveform. This can cause the device output signal eye to close even if the intrinsic signal from the device is jitter-free. Therefore, to perform any kinds of data modulation characterization, either on TL or μCL, a precise reference signal with low instrumentation jitter is required. The Agilent 86107A-040 Precision Time Base Module (see Figure 1) provides the lowest intrinsic oscilloscope jitter of industry standard and is in used tandem with any optical and electrical sampling modules to reduce mainframe jitter. The specifications of the Agilent 86107A-040 Precision Time Base Module is listed in Table II below.

Table II: key specifications of the Agilent 86107A-040 Precision Time Base Module[1]

Trigger Bandwidth	2.4 to 48.0 GHz
Typical jitter (RMS)	2.4 to 4.0 GHz < 280 fs 4.0 to 48.0 GHz < 200 fs
Time base linearity error	< 200 fs
Input signal level	0.5 to 1.0 Vpp 0.2 to 1.5 Vpp (typical functional performance)
Required trigger signal-to-noise ratio	≥ 200:1

Combined with the precision time base module our Agilent 86100C DCA-J wideband oscilloscope mainframe jitter can be reduced from 1 ps to levels below 200 fs. In this way, we are now capable to characterize the true jitter performance of our TL and μCL.

II 2. SHF 12103A Dual Differential Channel 56 Gb/s Bit Pattern Generator

Figure 2: SHF 10001A mainframe with a SHF 12103A bit pattern generator (redbox) and SHF 11104A error analyzer plug-in (not purchased in this grant)

The SHF 12103A is a dual differential channel 56 Gb/s BPG plug-in, which can be fitted into the SHF 10000 mainframes. It generates digital bit sequences such as standard pseudo-random bit sequences (PRBS) or user defined bit patterns at the data outputs ($Data$ and $\overline{Data}$). A wide range of operating bit rates from 6-56 Gb/s is covered by the generated data patterns. The dual channel BPG can generate up to two synchronized but independent data pattern outputs at 56 Gb/s per channel. Hence combined with the MUX module, it enables the broadband data pattern generation at speed above 100 Gb/s. Figure 2 shows the SHF 10001A mainframe with a SHF 12103A bit pattern generator (red box) and a SHF 11104A error analyzer plug-in (not purchased in this grant). In Table III we list the key specifications of the SHF 12103A dual differential channel 56 Gb/s BPG.

[1] Data Sheet of Agilent Infiniium DCA-86100C Wide-Bandwidth Oscilloscope –Mainframe & Module.

Table III: Key specs of SHF 12103A Dual Differential Channel 56Gb/s Bit Pattern Generator[2]

Parameter	Minimum	Typical	Maximum
Bit Rate (Gb/s)	6		56
Maximum Output Eye Amplitude (mV)	400	650	700
RMS Jitter (fs)		350	550
Rise/Fall (20% ~ 80%) Time (ps)			10.6
Crossing (%)	46	50	54
Duty Cycle (%)	47	50	53

III. SHF 12103A Bit Pattern Generator (BPG) instrument calibration and performance

The SHF 12103A Bit Pattern Generator provides a dynamic range of data rate, 6 - 56 Gb/s, and voltage output, 400 – 700mV and superior signal quality. It also has dual channels output which allows >100 Gb/s data rate with multiplexers. With the SHF 12103A Bit Pattern Generator, we have performed both electrical and optical eye diagram measurements. We also compared the electrical eye jitter characteristics at 56 Gb/s measured from our Agilent 86100C DCA-J scope with and without the 86107A-040 precision time base module.

III 1. Electrical Input Signal Eye Diagrams

The electrical eye diagrams measurement serves as a calibration test of the BPG and was performed under a direct connection from output of the BPG to our Agilent 86100C oscilloscope mainframe which includes the 86117A 50 GHz dual sampling head and the 86107A-040 precision time base module. The schematic setup for the electrical eye diagrams is shown below in Figure 3.

[2] Data Sheet of SHF 12103A Dual Differential Channel 56 Gb/s Bit Pattern Generator.

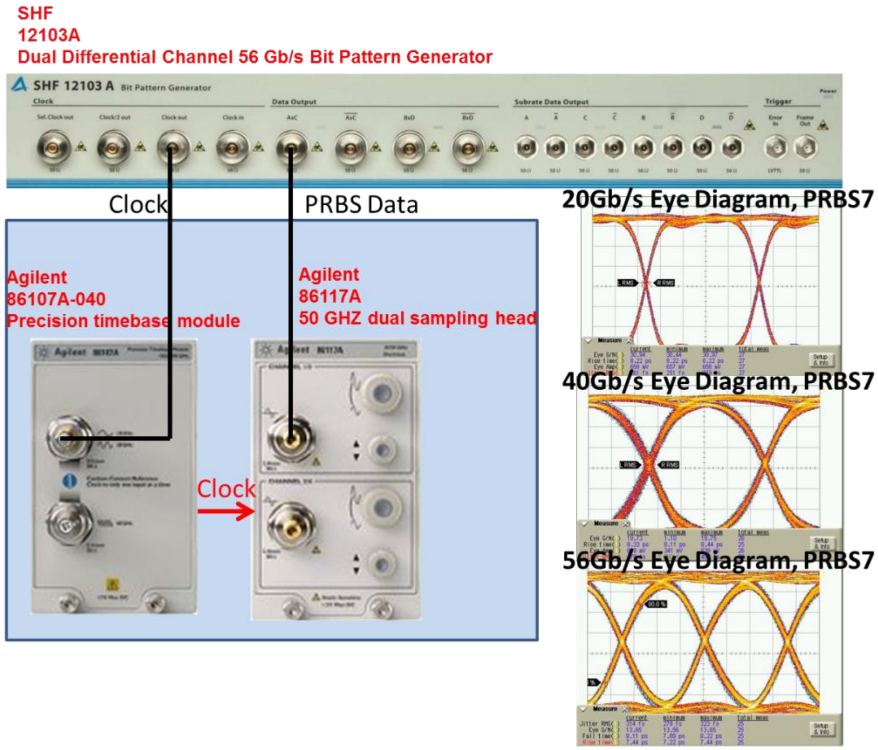

Figure 3: Experimental setup and 20, 40, 56 Gb/s electrical eye diagrams of the SHF12103A Bit Pattern Generator calibration test.

To ensure that the BPG is at optimal performance, we compared the parameters of the measured eye diagrams with the provided specifications. The detailed comparison is listed below in Table IV.

(Measured/Specs*)	SNR-Eye [#]	Risetime [ps]	Falltime [ps]	Output Eye Amplitude [mV]	Jitter(rms) [fs]
20Gb/s	30.94/29.8	8.22/X	N/A	658/691	261/X
40Gb/s	19.73/21.9	8.33/8.4	X/7.78	639/678	479/310
56Gb/s	13.65/15.6	7.44/7.89	8.11/7.44	X/660	314/280

Table IV: Comparison of HSIC measured parameters and provided specifications[3]. *Note that the provided specifications are at the standard of 80/20; whereas HSIC measured parameters is at the standard of 90/10, which provides a more rigorous and accurate characterization of eye diagrams

III 2. High speed data modulation performance of HSIC μCL

With the quality signal coming out of the BPG, we were able to further investigate the signal integrity of the optical output signal from our high speed μCL at

[3] Inspection Report of SHF 12103A Dual Differential Channel 56 Gb/s Bit Pattern Generator

data modulation rate higher than 50 Gb/s. In Figure 5, we show the experimental setup of our high speed data modulation testing. The device under the test is a HSIC 5μm oxide confined optical aperture μCL and the device L-I and optical spectrum characteristics are shown in Figure 4 below.

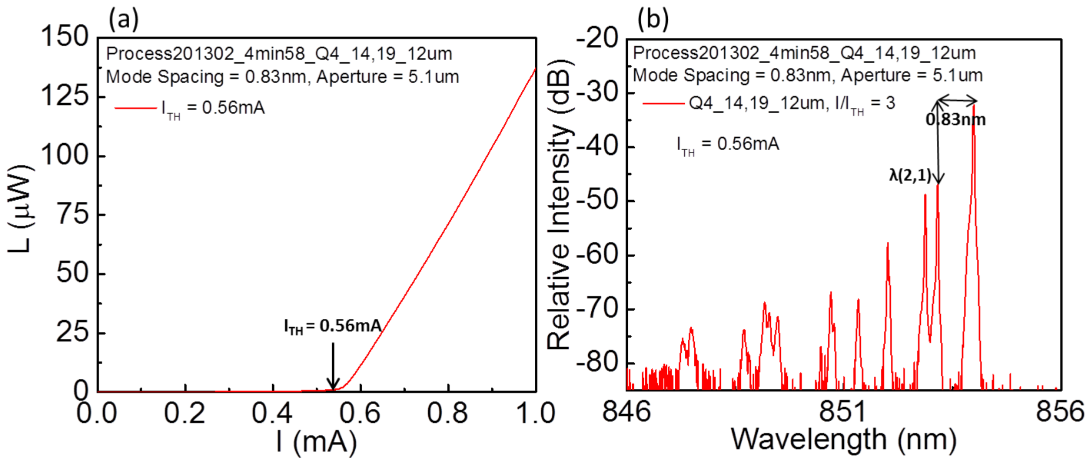

Figure 4: The (a) L-I and (b) Spectrum characteristics of the device under test. The laser threshold current, I_{TH}, of the device is 0.56mA. The mode spacing between the fundamental mode, λ(1, 1), to the first second-order mode, λ(2, 1), is 0.83nm which corresponds to an optical aperture opening of 5.1μm[4].

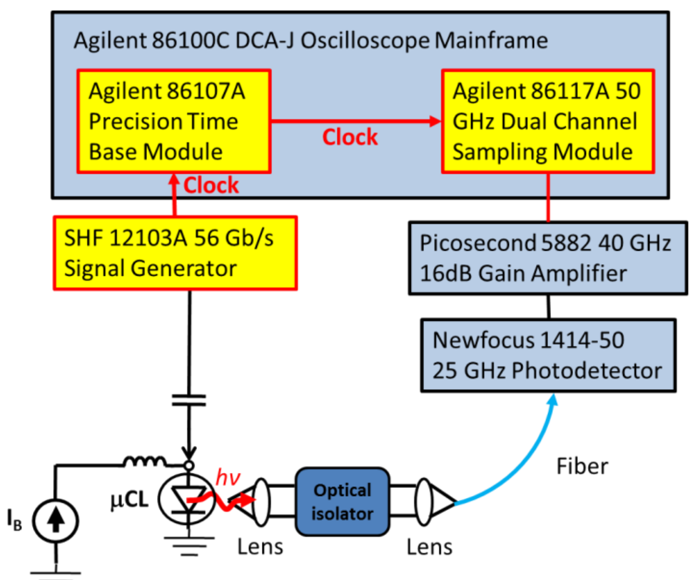

Figure 5: Experimental setup of optical output signal eye measurement with the purchased equipment

[4] C.H. Wu, F. Tan, M. K. Wu, M Feng, and N. Holonyak Jr., *Journal of Applied Physics*. **109**, 053112 (2011).

With the setup as shown in Figure 5, we measured the optical output signal eye of the device at various modulation data rate: 40, 44, 48 and 56 Gb/s. The transmission bit pattern is a non-return-to-zero Pseudorandom Binary Sequence with a length of 2^7-1 bits, which is in short called PRBS7. For the eye characterization, we took out the amplifier in the measurement in order to show the device intrinsic signal integrity. The measured eye diagrams are shown below in Figure 6.

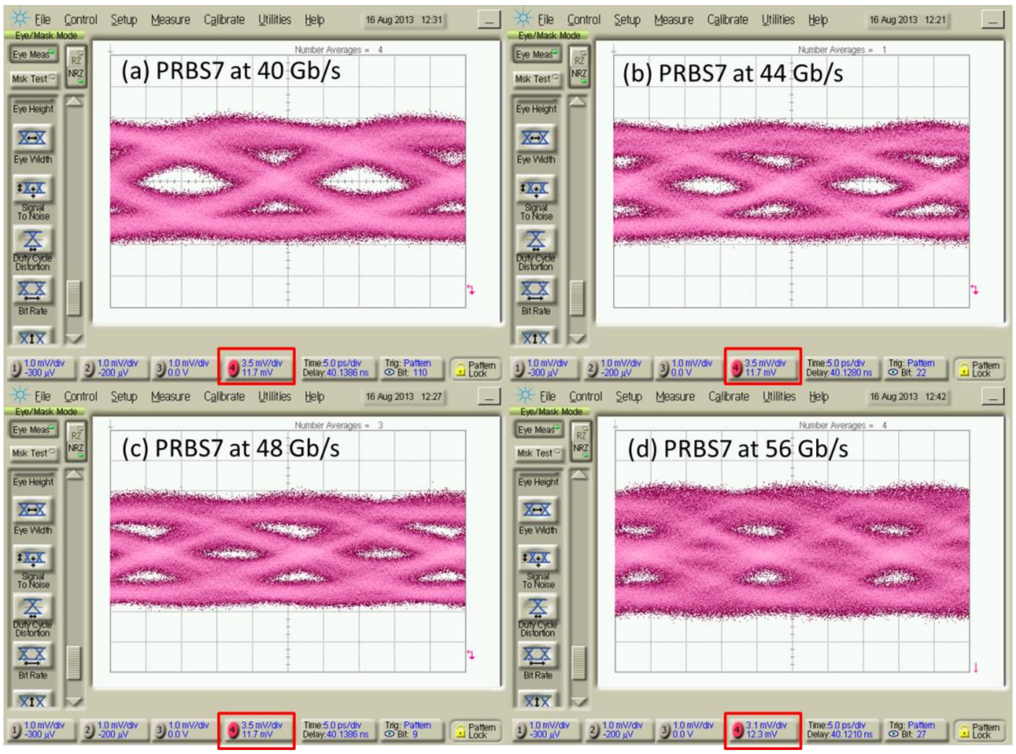

Figure 6: Optical output eye diagram of HSIC 5μm aperture VCSEL, without amplification, through a PRBS7 pattern at data modulation rates: (a) 40 Gb/s, (b) 44 Gb/s, (c) 48 Gb/s and (d) 56 Gb/s. The device is biased at I = 6 mA and the amplitude of the modulation signal is at Vpp = 575 mV for each data modulate rate

From the measured eye diagrams, we can see that the rise time and fall time jitter characteristics very clearly due to the new installed precision time base module. As the modulation data rate increases, the device bandwidth is not "fast" enough to respond to the modulation speed and hence the rise time and fall time falls short, causing the eye to close eventually at 56 Gb/s. Nevertheless, we can see that the eye is well defined and open at 40 Gb/s, at which we have demonstrated error free transmission[5]. The eye is slightly smaller at 44 Gb/s in the vertical axis but still is wide in the horizontal axis; therefore there is high chance that we can achieve error free transmission at 44 Gb/s

[5] F. Tan, M. K. Wu, M. Liu, M. Feng, and N. Holonyak Jr., *IEEE Photon. Technol. Lett.*, vol. 26, no. 3, pp. 282-292, 2014.

when we have the corresponding error analyzer. The eye is barely open at 48 Gb/s in both vertical and horizontal axis, and hence not very likely to pass error free test.

III 3. Optical Eye Signal Integrity with Amplification VS. without Amplification

On top of modulation speed characterization, we also characterized the optical output eye with amplification after the photodetector within the optical to electrical transmission link. As shown in Figure 5, the converted optical signal, into electrical, is amplified by 16 dB with the Picosecond 5882 amplifier. In Figure 7 below, we show a comparison of eye diagrams of the same μCL with and without amplification at 40 Gb/s PRBS7 data modulation.

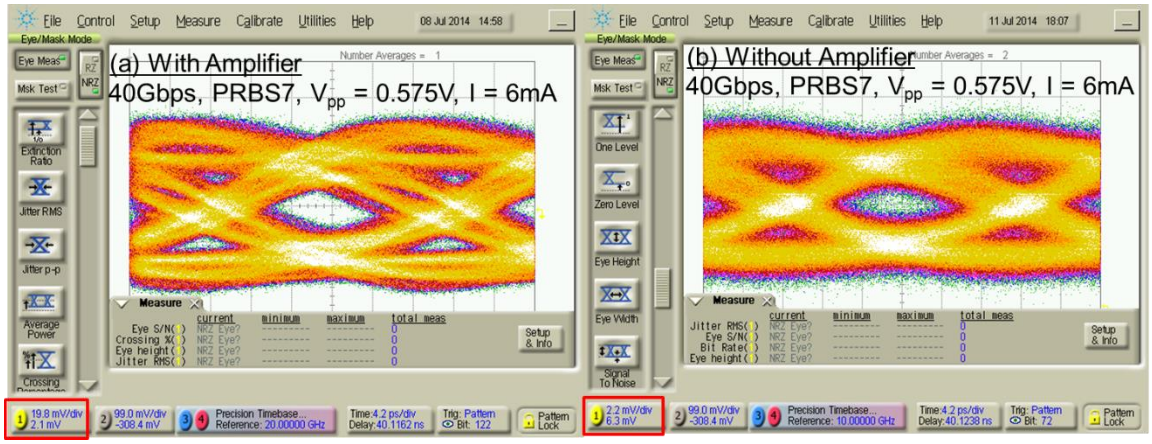

Figure 7: Eye diagrams with modulation rate of 40 Gb/s at I = 6mA and V_{pp} = 575mV (a) with amplifier and (b) without amplifier.

As we can see from Figure 7, the eye opening, particularly the eye height, is clearly larger with amplifier than without amplifier. The eye opening with amplifier is about 20 mV high and 6 ps wide, whereas the eye opening without amplifier is about 1 mV and 6 ps wide. On the other hand, the overshoot on the high-level and the jitter is lower without the amplifier; the amplifier introduces additional noise factor in the transmission system. However, in the receiver end of a communication transmission link, the eye opening area is the most crucial factor in sampling the received data. Hence, a setup that produces a larger eye opening will more likely lead to error free transmission.

III 4. Jitter Characteristics of Measured Electrical Eye at 56 Gb/s

With the Agilent 86107A-040 Precision Time Base module (PTB) installed, we were able to see an improvement in the jitter characteristics of eye diagrams on our 86100C DCA-J scope. We show the eye diagrams comparison below in Figure 8.

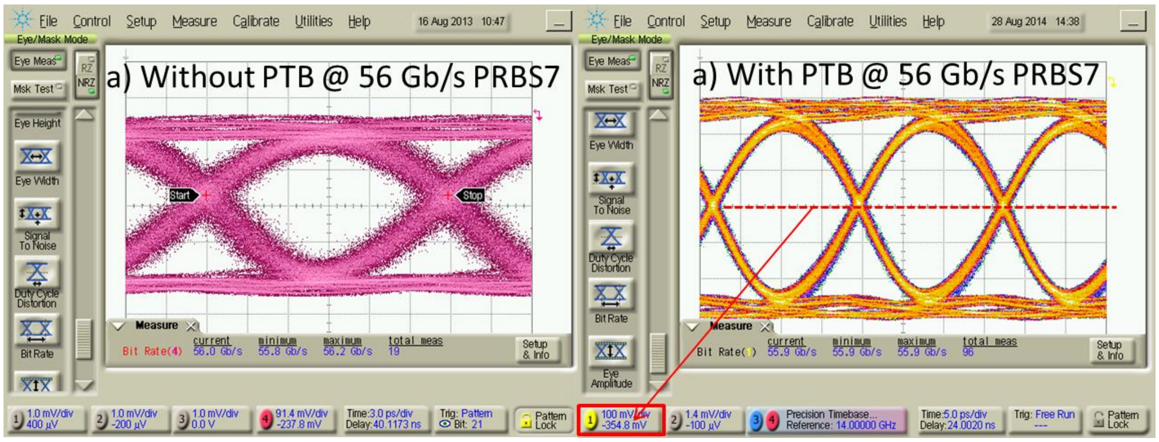

Figure 8: Electrical eye diagrams with modulation rate at 40 Gb/s (a) without PTB and (b) with PTB. A DC component of about -354.8mV is associated with the modulation data signal.

As we can see from the eye diagrams above, the fall time and rise time transitions are much cleaner, less jitter, with the installation of the PTB. The jitter (rms) without the PTB is about 6 ps whereas it achieves 0.314 ps with the PTB. We also noted there is a DC component, about -354.8mV, embedded with the AC modulation signal coming out of the SHF 12103 BPG. As shown in Figure 5, this DC component is blocked out by coupling capacitor when the modulation signal is injected into the devices.

Conclusion

With the purchased equipment from the grant, we have performed both electrical test and optical test of the testing system. The SHF BPG generated good quality signal data up to modulation speed of 56 Gb/s and there is a DC offset of about -354.8mV that needs be blocked out by a bias tee before being transmitted to the device. Our high speed μCL can produce open eye diagrams up to modulation speed of 44 Gb/s which indicates a good chance of achieving error free transmission. Although the eye diagrams above 44 Gb/s don't show an open area yet, we are working on a new generation of high speed μCL that aims to achieve error free transmission at modulation speed above 50 Gb/s.